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AN AUTOMATED LOW-EARTH ORBIT DETERMINATION SYSTEM WITH HIGH ACCURACY REAL-TIME CAPABILITY

BIOGRAPHIES

Dr. Stephen M. Lichten received an A.B. degree from Harvard University in astrophysics in 1978 and a Ph.D. from the California Institute of Technology in 1983 (in astrophysics), joining the Jet Propulsion Laboratory (JPL) also in 1983. Presently he is Group Supervisor of the Earth Orbiter Systems Group and a manager in the NASA Deep Space Network Advanced Technology Program. His work has emphasized GPS ground and space applications.

Mr. Ronald J. Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. As a member of the technical staff in the Earth Orbiter Systems Group at JPL, he has concentrated on the development of efficient filtering/smoothing software for processing GPS data and the processing, of TOPEX/Poseidon- GPS data.

Mr. Jeffrey M. Srinivasan received an A.B. degree in Engineering and Applied Sciences from Harvard College in 1983 and an M.S. in Electrical Engineering from University of Southern California in 1988. He joined the technical staff at JPL in 1983. He is currently a Technical Group Leader and a lead hardware/software engineer for the TurboRogue GPS receiver. He is currently adapting the acquisition algorithms and system software of the TurboRogue for various GPS and non-GPS applications.

Dr. Ulf J. Lindqwister received a Ph. D. in elementary particle physics from Princeton University in 1988, when he joined JPL. He is presently Group Supervisor of the GPS Network and operations Group. His work has focused on geodetic GPS applications, developing in-receiver autonomous capabilities, operation of NASA's stations in the international GPS Service (IGS), and developing techniques for study of the Earth's ionosphere

Mr. Timothy Munson has been a member of the technical staff at JPL since 1984. He is responsible for the operation of the TOPEX/Poseidon GPS flight receiver.

Dr. Sien-Chong Wu received his B. S. E.E. from the National Taiwan University, Taipei, Taiwan, and his Ph.D. from the University of Waterloo, Ontario, Canada. He is currently a Technical Group Leader in the Earth Orbiter Systems Group at JPL. He has been involved with the development of tracking systems for deep-space as well as near-Earth space vehicles, and their applications to precision geodesy. his current interest is in the area of precise orbit determination using GPS.

Dr. Bruce Haines received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the TOPEX/Poseidon Joint Verification and Precision Orbit Determination Teams, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

Mr. Joseph Robert Guinn attended the University of Texas at Austin and obtained BS and MS degrees in Aerospace Engineering. As a member of the technical staff at JPL, he is working on tracking and navigation of planetary and Earth orbiting, spacecraft, including precision orbit determination and trajectory analysis for the TOPEX/Poseidon ocean topography experiment.

Dr. Lawrence Young received his Ph.D. in Nuclear Physics from the State University of New York at Stony Brook in 1975, and has worked at JPL since 1978. Currently Group Supervisor of the GPS Systems Group, his research includes development of high precision radio interferometric tracking techniques, nanosecond-level clock synchronization with both VLBI and GPS, design and development of several high precision GPS receivers, and various scientific GPS applications. He has initiated work on custom GaAs chip design to enable improved radiometric performance, and has worked with system studies aimed toward improving the performance of spacecraft ranging systems.

ABSTRACT

GPS-based tracking is increasingly becoming the tracking system of choice for low-Earth orbiters (LEOs). With flight GPS instrumentation, LEO tracking and orbit determination functions can be highly automated. Automation in the tracking and navigation process offers potential to simplify current procedures and lower operational costs. Significant advantages in performance are also possible with GPS-based techniques.

A wide range of configurations for GPS-based LEO tracking will be presented in this paper. Tracking and navigation accuracies range from hundreds of meters for the simplest approaches, to 10 cm for the most elaborate. The simplest consists of a minimal GPS flight instrument requiring only a fraction of a watt power and a few hundred grams mass. Better performance can be achieved with a more conventional GPS flight receiver. For the best accuracy, data from ground GPS trackers can be combined with the flight data. Even when ground data are incorporated, the whole process can be highly automated and accomplished in near-real time. This paper includes

results from a recent demo for a LEO where such automated data acquisition and processing, were demonstrated and better than 1-meter real-time knowledge of the orbit was achieved with both anti -spoofing, and selective availability on.

This work should be of interest to various government agencies, including NASA and the military, as well as to the private sector, because it describes configurable automated orbit determination systems utilizing GPS to provide orbit knowledge, in real time to between 1 and several hundred meters accuracy, depending on a number of design factors. The focus of the paper is on tracking techniques which would be viable for small spacecraft, which are expected to dominate NASA's low-Earth missions in the coming decade.

INTRODUCTION

The development of low-cost satellite tracking and orbit determination systems is currently receiving increased emphasis in government agencies such as U.S. National Aeronautics and Space Administration (NASA), the U.S. Air Force (USAF), the Navy, and also in the private sector. A combination of factors is responsible 'for this recent trend. These include:

- A greater number of LEOs will be tracked by NASA's Deep Space Network (DSN), which is operated by the Jet Propulsion Laboratory (JPL), while operations budgets for such activity are not expected to increase.
- NASA is increasingly emphasizing the use of smaller, less expensive satellites and flight systems.
- Communications satellite systems comprised of constellations of LEOs are being developed in the private sector. An automated, low-cost capability to maintain constellation configurations and determine ephemerides will be needed to minimize operations costs.
- The USAF is currently examining ways to lower the. operations costs for tracking and orbit determination in the Air Force Satellite and Control Network (AFSCN).
- The U.S. Navy is using low-Earth orbiting satellites for a variety of applications, sometimes requiring precise, ephemeris knowledge in real time or near-real time.

In this paper we shall discuss GPS-based flight (and flight+ground) tracking systems where data acquisition and processing are highly automated, minimizing operations costs. GPS can provide real-time attitude determination, timing calibration, and orbit determination at a range of accuracies. JPL recently finished a demo of real time and near-real time. sub-meter orbit determination for a LEO in a highly automated system, Results from that demo will be shown in this paper.

LOW-EARTH TRACKING TECHNIQUES

A number of different LEO tracking techniques are currently being used by NASA, the U.S. military, and by the private sector. These include (Fig. 1):

(1) Doppler and ranging from ground stations

(2) Angle data from ground stations

(3) Radar

(4) TDRSS (Tracking Data and Relay Satellite System)

(5) GPS tracking with flight instruments

(6) GPS tracking with flight+ground instruments

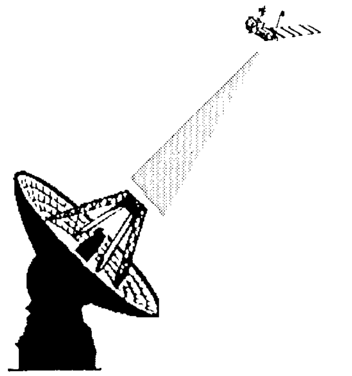

Fig. 1a Traditional ground-based tracking (Doppler, ranging, and angle tracking data) with large ground antennas.

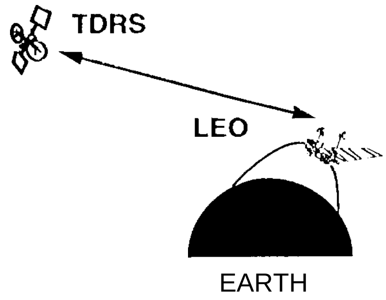

Fig. 1b Low-Earth tracking with TDRS.

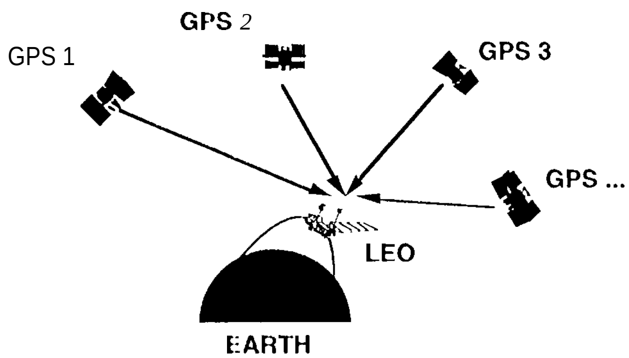

Fig. 1c GPS-based tracking with flight receiver.

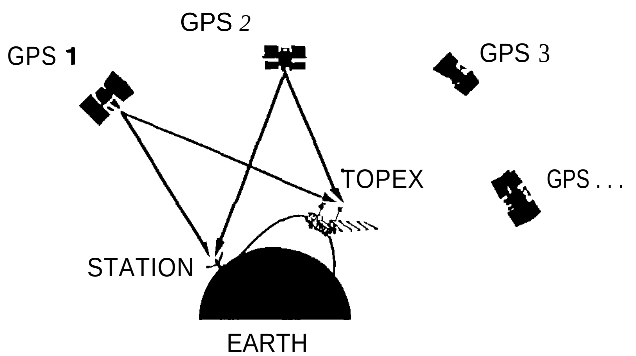

Fig. 1d GPS-based tracking (flight+ ground receivers).

Traditional ground-based techniques [(1)-(3)] often utilize ground antennas of size ~ 5 to 30 meters. The cost of operating such systems can range from a few hundred to several thousand dollars per hour. This is due partly to the size of the antennas, the complexities in scheduling and performing the observations, and the. costs of data processing. In the United States, radar observations (3) are processed by the military (NORAD) and made available through a dial-up bulletin board to outside users. LEOs carrying TDRS transponders (4) can be scheduled for service to provide telemetry and orbit determination support. TDRS is a geosynchronous satellite system maintained by NASA.

The GPS-based techniques [(5)-(6)] utilize data from the Global Positioning System, a constellation of 24 Air Force navigation satellites in 12-hr orbits. GPS-based tracking, is distinctly different in character from the. other approaches in several fundamental ways:

• GPS data are acquired with small, commercially available receivers[1] and antennas, several inches in size. The operational costs can be very low since GPS receivers can run continuously and do not normally require commands, scheduling, or inputs from operators, in contrast to the larger ground antenna systems [(1)-(3)]. On the other hand, projects must consider the initial cost of procuring, GPS receivers. Ground receiver costs range from ~ $0.5 5K-$50K, while flight receivers are available commercially for ~$ 100K-$1000K[1].

• The GPS-based techniques perform independently of the number of users of the system, while the other tracking, systems have reduced availability and degraded performance as the number of users increases.

• Range of performance options: the. GPS techniques offer users a wide range of capabilities, as described below.

Performance Comparison

Fig. 2 compares traditional ground-based tracking techniques (NORAD, 1- and 2-way Doppler) and GPS for a LEO at about 600 km altitude., The figure shows real-time orbit determination knowledge typically available from each technique, and is based on a combination of actual results and covariance analysis. The covariance studies depend in large part on certain assumptions. It was assumed that the 1- and 2-way Doppler ground data, or the angle data, could be collected, processed, and turned around in less than 6 hrs, with real-time knowledge provided by a predicted ephemeris. Either one or two ground sites were assumed, with 1-5 passes per day at each site. The angle data were assumed to have random noise errors of 30-300 mdeg. The satellite was assumed to have a good on board oscillator for the 1-way Doppler ($10^{-10}/\sqrt{sec}$). NORAD data are collected and processed by the USAF, with the ephemerides then posted and retrieved by users after the fact and a predicted orbit used for real-time knowledge. GPS receivers provide real-time positions at the 50-100m level every second. An improved GPS system would provide a simple filter to fit and smooth data over several hrs to a day and then predict to real-time. Not shown on the plot are results for TDRS-based orbit determination for LEOs. TDRS supports real-time low-Earth requirements in the range of 0.05-10 km, depending heavily on the amount of contact time with the TDRS satellites and on the user orbit (R. Hart, Goddard Space Flight Center, private communication, 1995).

Some low-Earth satellites have a location requirement based solely on the need to acquire the spacecraft with a ground antenna for periodic communication and telemetry exchange. Depending on the size of the ground antenna and its beam size, real-time knowledge at the level of several km would be adequate for this purpose for S-band tracking. Some satellites have a requirement to follow a more precise. specific ground track or orbit for surveillance, scientific data acquisition, or to maintain a satellite constellation. These more precise requirements are mission specific and may call for sub-100 meter knowledge, or even sub-meter knowledge of the satellite trajectory in real time or near-real time. in addition, LEOs typically require some knowledge of the. onboard clock offset and knowledge and control of the spacecraft attitude in real or near-real time. In general, attitude and timing data are not provided by any of the tracking, systems being discussed here except for GPS, which provides precise timing information and can, with appropriate system design, provide attitude information[2].

[1] A number of companies offer, or have announced their intention to offer, flight GPS receivers. At the time this paper was prepared, at least one had announced a flight qualified unit.

[2] While this paper focuses on orbit determination, the attitude and timing estimation capabilities of GPS instruments are an advantage as they may enable elimination of other on board systems for these functions, thus lowering cost.

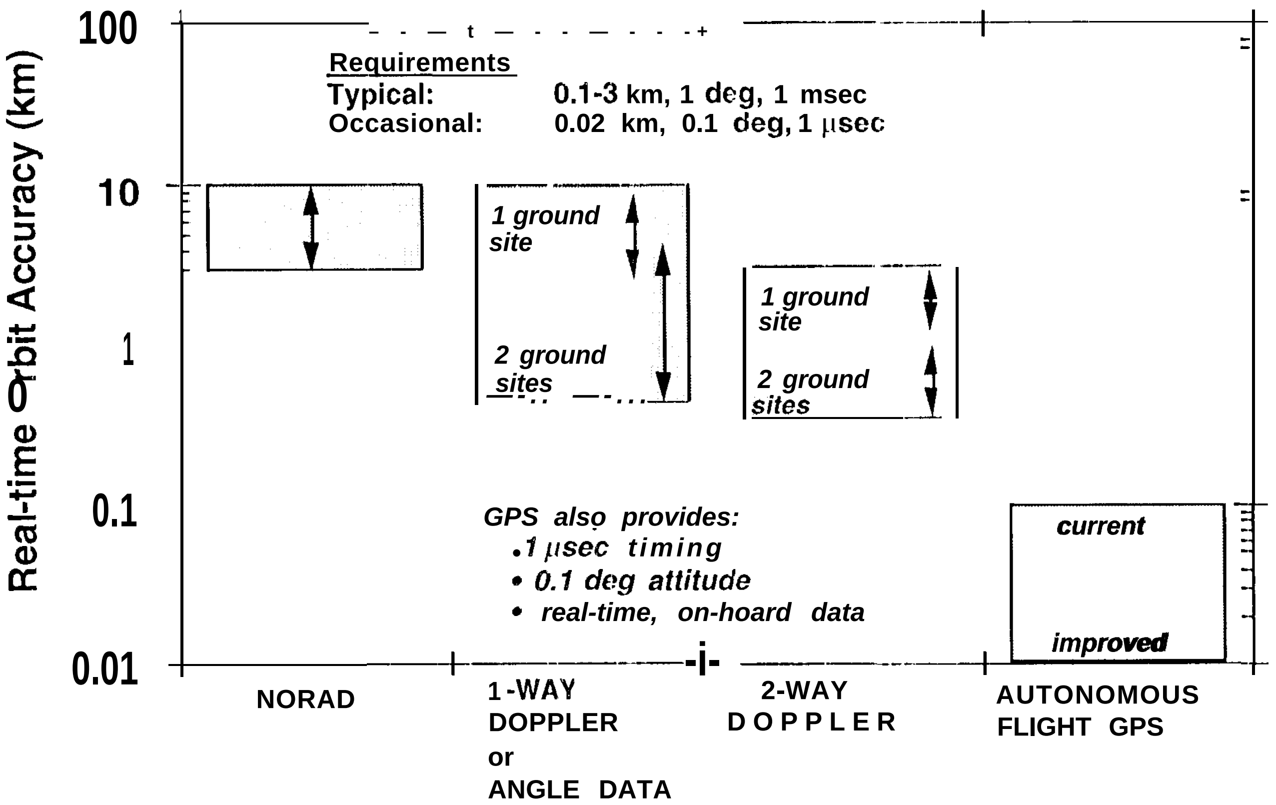

Fig. 2 Expected real-time performance for ground-based orbit determination of a low-Earth orbiter and for GPS-based tracking. One-way Doppler analysis assumes fairly high-quality frequency standard on board ($10^{-10}/\sqrt{sec}$). Not plotted are the results for "TDRS-based tracking. TDRS provides orbit determination at the level of 0.0S to 10 km, depending on the user requirements and the amount of TDRS contact time available.

Operational Considerations

Satellite missions with relatively loose navigation requirements can in principle rely cm NORAD's posted ephemerides for their operations. The USAF has placed some restrictions on the use of this resource, however, and as tbc NORAD bulletin board becomes increasingly congested with user requests, additional restrictions could be placed on its use. In addition, NORAD does not guarantees the accuracy or timeliness of its ephemerides. For missions willing to accept these uncertainties, NORAD is obviously a very low-cost method of obtaining coarse location information about a space vehicle..

The use of Doppler (and range) or angle data at conventional ground tracking site.s can generally meet the accuracy requirements of most missions, at least in the several hundred meter to few-km regime. The cost of operations at these ground tracking complexes is fairly high, however, in the range of hundreds to thousands of dollars per hour for individual antennas. Each satellite tracking pass usually has unique. calibration and configuration requirements, requires ground operations teams, and must be scheduled on a limited number of relatively large antennas (5-30 meter size). Tbc number of LEOs tracked is expected to dramatically increase in the next ten years, at least for NASA missions tracked by tbc DSN. The complexity of scheduling is not only an inconvenience but also a significant operational expense itself, and without alternate tracking systems, additional ground antennas and complexes will have to be built. JPL has been studying this problem extensively with a goal of investigating lower-cost tracking options.

GPS-based tracking techniques for navigation can reduce operations costs since tbc positioning information is available on board, in real time, with little or no ground activity or input. As will be shown below, nearly all the. processing associated even with extremely precise orbit determination with a GPS fright receiver + ground net can be highly automated. Flight GPS-based tracking systems arc configurable and can be adapted to provide accuracies ranging from i O cm to hundreds of meters, using average power between about 10 watts down to less than 0.1 watt. Some of these options arc described in the next section. Standard positioning, service (S1'S) users of GPS can count on the policy of the U.S. government as specified in the "GPS Standard Positioning Service Signal Specification" [Paige I 993], where it is stated that GPS is tbc DOD's primary radionavigation system well into the next century. That Specification also states that all users worldwide will have available to them the Standard Positioning Service (S1'S) which will provide horizontal positioning accuracy within 100 meters (95% probability) and 1 56 meters vertical (95% probability), and timing accuracy within 340 nsec (950/0 probability). In practice, GPS has proven to be a very reliable system. GPS receivers usually provide solutions every second and they work passively - no pointing or scheduling is needed. The commonly used omnidirectional GPS antenna provides ample continuous visibility of GPS satellites for positioning and orbit determination.

GPS can reduce (or eliminate) much of the demand for ground antennas for tracking and navigation, but ground antennas are still needed for data communications (telemetry). However, new low-cost telemetry systems being studied do not require. large antennas at all. JPL has recently demonstrated a prototype Telemetry and Tracking System which consists of a low cost (<$200k) weather satellite ground tracking station with a small (few-lncler) size antenna, The purpose of the system is to provide unattended and continuous retrieval of science data telemetered from LEOs. The demonstration showed that a workstation controlling the system can automatically track and receive science telem try from specified earth orbiters during overflights of the ground station location, An additional feature of this demonstration was the automatic distribution of the downlinked data to the personal computer of the cognizant Principal Science investigator, also via commercial phone lines [N. Golshan and W. Rafferty, personal communication 1994]. The JPL . prototype telemetry workstation was recently demonstrated with automatic retrieval of NORAD ephemerides for satellite acquisition.

The NASA TDRS system also offers satellite users a space- based means of orbit determination (and telemetry support) through Doppler and ranging with the. TDRS geosynchronous satellites. The TDRS transponder, however, typically requires 20-40" watts power and has mass of about 7 kg. For very small satellites, these power and mass numbers may be difficult to accommodate. TDRS satellites are available for limited times and a limited number of customers can be serviced. The Space Shuttle and several classified users have a high priority in the scheduling of TDRS contact time. Therefore, scheduling is also a major concern for use of TDRS.

GPS TRACKING SYSTEMS

GPS-based tracking systems for orbit determination offer a wide range of configurations for low-cost, highly automated operations, in this section, these configurations are discussed and some results will be presented.

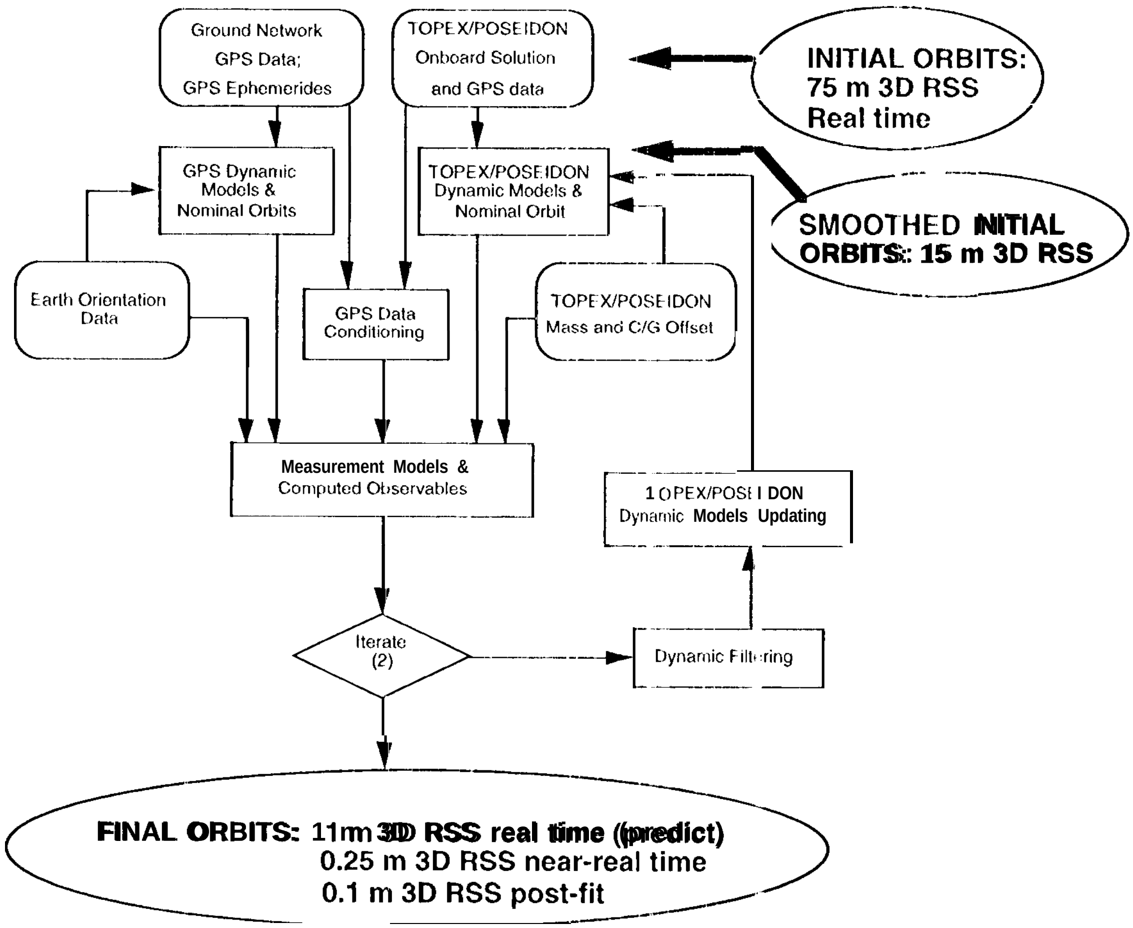

Fig. 3 Data processing flow for automated low-Earth orbit determination with GPS (TOPEX/Poseidon).

TOPEX/Poseidon Automated Tracking Demo

Fig. 1 d shows the highest accuracy GPS-LEO tracking configuration. A network of ground receivers and the low-Earth orbiting flight receiver simultaneously track GPS satellites. J]']. has developed an automated system for data retrieval and processing from the flight and ground receivers. This system was recently tested with the TOPEX/Poseidon ("1'/1') satellite at 1336 altitude over a 14-day period in the fall of 1994 as part of an experiment sponsored by the Naval Oceanographic Office. Fig. 3 shows the overall process for data collection and processing. JPL's GIPSY-OASIS II software was used for the orbit de.termination (Bertiger et al. 1994; Muellerschoen et al. 1994).

The ground network includes receivers operating continuously as part of the International GPS Service (IGS) described by Zumberge et al. 1994. At 0^h UTC JPL's automate.d communications software activates several modems, which dial up a subset of the. 60+ IGS sites and copy the GPS ground data from the previous day. A few hours later, internet connections are made to sites where internet is available and the previous day's data arc copied from those sites-[3]. in coordination with the automated retrieval of global ground GPS data, the flight GPS data from '1'/1' for the previous day are seat to J]']. from NASA via the TDRS system through White Sands, NM, and the Goddard Space Flight Center. GPS flight data from T/1' typically arrive at J]']. 3-5 hrs after real time. The GPS data arc checked and preprocessed to remove outliers and connect phase. Within several minutes after the data have arrived at JPL, by smoothing and least-squams fitting the GPS broadcast ephemerides and the once per sec re.al-time (accurate to 75 m) on board navigation solutions from the T/P flight GPS receiver, nominal et-bits for the GPS satellites and for the LEO ('1'/1') can be determined. Measurement models and partials arc computed and a square-root information (Kalman-type) filter is run to perform a least squares fit to the GPS pseudorange and carrier phase. The filter solves for more precise GPS and 1,110 orbits simultaneously. Typically two iterations were performed for each daily solution during the 14-day test, during which anti-spoofing was on. The entire process was automated with an expert system relying primarily on UNIX utilities (such as c shell, awk, and sed). The executive script runs each portion of the software as the previous step is completed. There are many levels of built-in data checking, quality control, and consistency checks. The system is data driven and runs continuously from one day to the next, pausing only to wait for the arrival of the next day's data. Part of tile system is described in Wu et ai. 1993.

In an earlier experimental phase. of 'i'/}' GPS processing at JPL, precise solutions were typically obtained at least onc week after real time. This was due in part to the fact that onc goal of the precise orbit determination (POD) GPS experiment on T/1' was to achieve best accuracy possible for the radial component of the orbit. Therefore it was desirable to wait for data from at least a dozen sites (recently it has been shown that the results improve with data from 20 or more sites) and in some cases data were reprocessed to improve orbit quality. The most accurate GPS solutions determined for T/P at JPL are accurate to about 2 cm radially and 10 cm in cross- and down-track components (Wu et al. 1993; Bertiger et al. 1994). When anti-spoofing, was activated, as it was during the 14-day automated processing test, the T/1' flight receiver switched into L1-C/A mode, which degraded the final best GPS-based orbits to about 4 cm radially and 15 cm overall (Muellerschoen et al. 1994).

For the 14-day quick-look demonstration of automated processing, the data processing began automatically when a minimum of 5 sites (+ '1'/1') had delivered data to JPL. The quick-look orbits were produced and automatically delivered electronically by JPL to the Navy sponsor by 10 am local time (17:00 UTC) for the previous day. By propagating the orbits ahead in time, both real-time and predicted ephemerides for the LEO were obtained. Each automated daily solution during the 14-day test period spanned 27 hrs, with 3 hrs of overlap with the previous day. One measure of precision for the near-real time automated solutions is the rms difference between adjacent daily solutions during the 3-hr overlap period. These rms values arc plotted in Fig. 4.

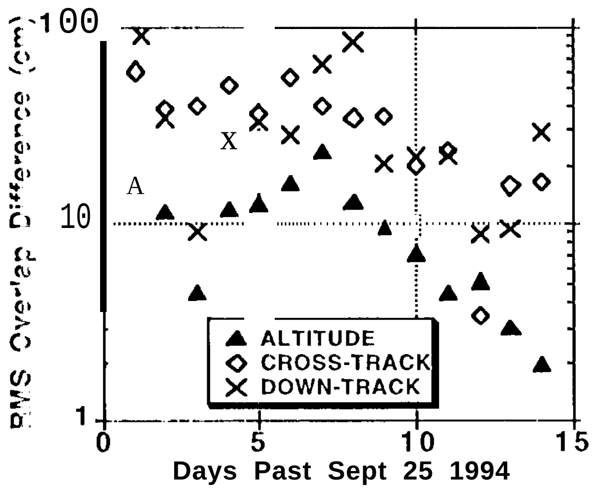

Fig. 4 Overlap (3-hr) rms differences for daily solutions in the 14-day automated TOPEX/Poseidon near-real time orbit determination demonstration.

A comparison between the quick-look '1'/1' orbits and the final, precise GPS-based orbits also provides a measure of the accuracy of the automated quick- look orbits, since the final GPS-based orbits have. been verified with independent ranging and Doppler tracking data and been shows to be accurate to about 15 cm (RSS 3D) when **AS is on** (Muellerschoen et al. 1994). That comparison indicates that the quick-look et-bits for '1'/1' from the 14-

[3]Note that the internet connections are delayed several hours in order to reduce loading on the J]']. computers. 1 'or faster data turnaround, the internet connections could be scheduled earl icr with a dedicated computer.

•

day demo were accurate to better than 25 cm, averaged over all 14 days, consistent with Fig. 4.

Each daily solution was propagated into the future 5 days. Since the generation of the orbits took less than 24 hrs, the 1-day predicted ephemeris compensated for the data turnaround delay and was, in effect, a real-time orbit estimate. These real-time estimates (1-day predicts) agreed with the final, precise orbits typically to better than 1 meter. The orbit predictions (out to 5 days in the future) are shown for 'T/P' for the first six daily solutions of the 14-day test (only six [instead of the nine possible.] are shown due to a T/P maneuver near the end of the 14-day period) in Fig. 5. Thus the quick-look automated processing of data from T/P (plus a minimal number of ground sites) shows that sub-meter real-time orbit estimation is feasible. The determination of accuracy in Fig. 5 was a blind test, since the quick-look solutions were determined within several hrs of real time and were recorded days before the final, precise "truth" solutions were available. Note also, however, that the altitude (1 336 km) of T/P minimized effects of drag and the T/P project developed and tuned an extremely precise gravity field f-or the mission. Other sate.tlites at lower altitudes would probably have a somewhat higher real-lime orbit error using this prediction technique due to higher errors from gravity and drag. These could be minimized, however, by turning the data around faster to reduce the required prediction interval for real-time knowledge.

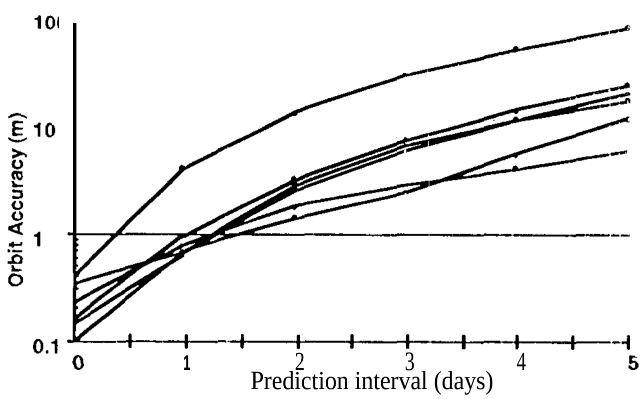

Fig. 5 Quick-look T/P orbit predictions for six daily solutions, each propagated 5 days into the future. Since the data were processed in less than 24 hrs, the 1-day predicts provided real-time orbit estimates. Note that 5 out 6 isolations showed sub-meter accuracy for the 1-day predicts (real-time orbits).

Configurable Receiver Architectures

Spacecraft and spacecraft instrument designers must select from a continuum of options that seek to balance oft-conflicting performance and "cost" constraints. Typically, the "costs" are power consumption, mass, as well as actual cost of development, fabrication, test, and operation. JPL is investigating several GPS receiver architectures that are readily scalable and offer a convenient way of trading off power/cost/mass constrains against navigation performance requirements. Performance can refer to real-time position accuracy as well as ultimate knowledge of the orbit which can be gained through inclusion of ground network data and post-processing. The architectures presented herein address both definitions. They are intended to offer the space system designer a wide range of choice when inclusion of a flight GPS receiver is desired.

The simplest receiver architecture is illustrated in Figure 6. It offers a miniaturized receiver with extremely low power consumption in exchange for reduced accuracy. This reduced power is achieved by only collecting very short lime samples of GPS data a few times per orbit. When the optional GPS processor is included, it would operate on these stored bits and produce a point position after each collection time. Alternatively, in exchange for even more simplicity and lower power consumption, the on-board processor can be eliminated and the stored GPS signal samples telemetered to the ground for post processing. This option reduces spacecraft autonomy, increases downlink bandwidth requirements, and introduces latency in orbit updates; all of which may be acceptable for spacecraft with severe power/mass limitations. in addition, this simple architecture can offer a low-cost, backup mode to any flight receiver; at any time a short interval of antenna data can be captured and downlinked to the ground for analysis and health assessment. This architecture has not yet been demonstrated, but performance has been verified in computer simulation (Figs. 7-8).

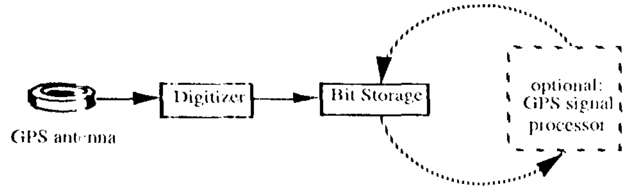

Fig. 6. Functional Block Diagram of ultra-low power architecture

Architecture Description	Accuracy	Power
Digitize, store, & forward to ground	~ 200 m	<0.1 w
Digitize, store, & process	-200" m	<0.5w
L1 sparse data & fit to orbit	-100111"	~ 1w
L1 continuous data, point positions	50-100 m	~4w (c)
L1 continuous data, filter/fit orbit	10-20 m	-4W (c)
L1/L2 continuous+groundnet	0.1 m	6-8w(c)

Fig. 7 Comparison of different GPS flight instrument architectures for performance and average power ["(c)" denotes **continuous power]. Accuracy is for real-time knowledge, except for the last entry.**

Fig. 7 lists receiver configurations which offer a wide range of performance/power consumption compromises. The underlying architecture for all these configurations is based on the geodetic quality, dual-frequency ground receiver developed by JPL, which was the basis for several flight receivers currently in development. A key advance in the technology is the inclusion of power management features in the receiver architecture, enabling the receiver to selectively turn off various components when not in use to reduce power consumption. 11 can also vary the clock speed of the controlling microprocessor and the data rate of the GPS signal processor to meet a specific performance goal with the minimum power usage. Per unit costs for these options in Fig. 7 for future missions could range from as little as a few tens of thousands of dollars for the simplest option (digitize, store, and forward) 10 hundreds of thousands of dollars for the 1 1/1.2 flight receiver - assuming fully space qualified units. Exact costs will depend on the rapidly changing commercial situation, but there is a clear relationship between performance, power required, and dollar cost.

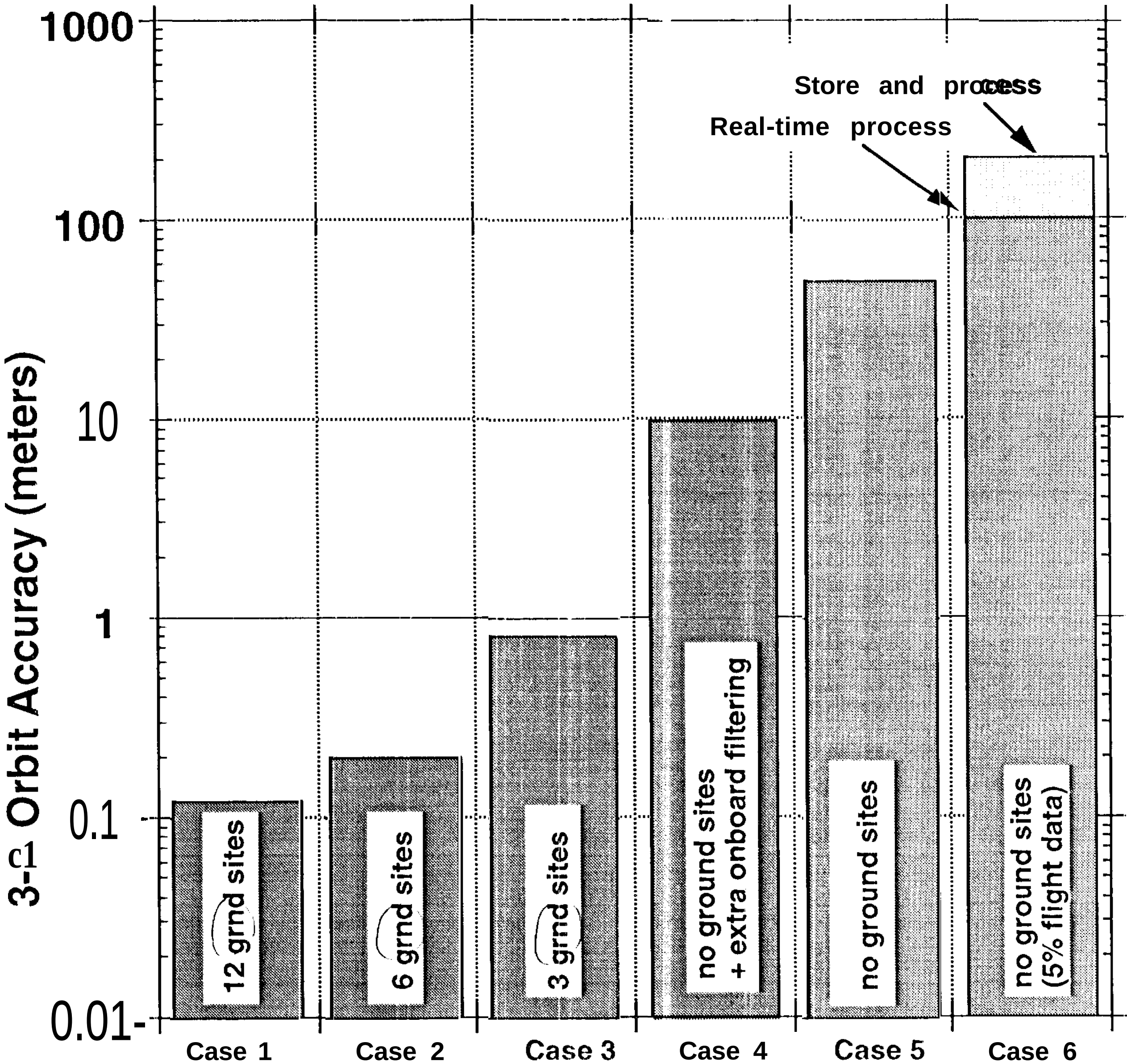

Figure 8: Comparison of low-Earth orbit accuracy for different strategies. Case 1 corresponds to the precise, post-fit solution for T/P with G]%; cases 2-3 represent the demonstrated real-time capability with automated processing with minimal ground net plus flight '1'/1' L1-C/A code receiver. Cases 4-6 have no ground data included: case 4 incorporates extra filtering parameters to reduce errors from the fifth case (state-only filter on board), and the last (sixth case) includes only S minutes of data every 2 hours (such a strategy could save power on a future mission). Cases 1-4 are from 'I'/I' experimental data, and cases 5-6 are based on JPL tests and simulations r-an with data from T/P and from the 560-km altitude TAOS satellite. The higher error for the delayed processing (versus real-time processing) for case 6 results from additional dynamic error (drag, gravity) from the orbit prediction to real-time,

Fig. 8 summarizes the full range of GPS configurations discussed in this paper and expected capabilit ies. Cases 1 to 6 show increasingly simplified tracking and orbit determination scenarios, all relying on GPS and all capable of being highly (if not totally) automated. The extreme of case 6 would have a very low-cost, simple few-hundred gram GPS flight instrument (top entry in Fig. 7) with less than 0.1 w average. power requirement. Due to the delay in processing, this approach can be expected to provide a few hundred meters accuracy in real time, as opposed to - 100 m with immediate processing. Case *5 shows* performance with real-time on board solutions from a flight GPS receiver, while case 4 incorporates, in addition to case 5, a simple on board filter to perform a running dynamic fit to improve accuracy. Cases I -3 show tbc improvements resulting from the incorporation of ground GPS data. With such ground data available in near-rca] time electronically from existing international consortiums such as the IGS (Zumberge et al. 1994), the additional expense is minimized. JPL's 14-day quick-look demo with "1'/1' shows how such processing can be highly automated.

CONCLUSIONS

A variety of highly configurable G1'S-based low-Earth tracking systems arc being studied at the Jet Propulsion Laboratory. The GPS-based systems all rely on some form of GPS flight instrument, and for the ultra-precise applications, can also incorporate data from ground GPS receivers. The systems being studied and developed at JPL incorporate high levels of automation to minimize operations costs. A recent demonstration using L1-C/A GPS data from the TOPEX/Poseidon low-Earth orbiter showed that real-time knowledge of the orbit to better than I meter is feasible in an automated GPS processing, system without knowl edge of the selective availability or anti -spoofing codes. The studies also show that a trade can be made for coarser accuracy with simpler, lower power, and lower-cost systems. A highly simplified, very low-cost GPS fright unit requires less than 0.1 watt average power and can provide a few hundred meter real-time knowledge of the LEO orbit with automated processing. in between these extremes lies a wide range of possibi i it its, some with all orbit determinat ion performed on board the sat ellite. The conti nued development of GPS technology and related tracking, techniques will enable government and commercial organizations to support a growing number of low-Earth orbiters at lower cost, while at the same time reducing reliance on older, more expensive, traditional methods of tracking, and orbit determination.

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REFERENCES

Bertiger, W.]., Bar-Sever, Y.E., Christensen, E.J., Davis, 1{. S., Guinn, J.R., Haines, B. J., Ibanez-Meier, R.W., Jee, J. R., Lichten, S. M., Melbourne, W. G., Muellerschoen, R. J., Munson, I. N., Vigue, Y., Wu, S. C., Yunck, 2'.1'., Schutz, B.E., Abusali, P.A.M. , Rim, H. J., Watkins, M. M., and Willis, 1'., "(ii'S Precise Tracking Of Topex/Poseidon: Results and implications," *JGR Oceans Topex/Poseidon Special Issue*, Vol. 99, 1 Dec. 15, 1994, in press.

Muellerschoen, R. J., Bertiger, W., Wu, S. C., and Munson, 'r., "Accuracy of GPS Determined TOPEX/Poseidon Orbits During Anti Spoof Periods," *Proceedings of the 1994 National Technical Meeting, Inst. of Navigation, San* Diego CA, Jan. 2426, 1994, pp. 607-614,

Paige, E., Jr., "Global Positioning System Standard Positioning Service Signal Specification, " Letter of Promulgation from Assistant Secretary of Defense, U.S. Pentagon, Dec. 8, 1993 [OASD(C3I)/T& TC3, 6000 Defense Pentagon, Washington 1).C. 20301-6000].

Wu, S. C., Muellerschoen, R. J., Bertiger, W.]., Yunck, 1'.1'., Bar-Sever, Y.E., anti Munson, 'l'. N., "Automated Precision Orbit Determination for TOPEX/Poseidon with GPS,' AAS/AIAA Astrodynamics Specialist Conference (Proceedings, paper AAS 83-576), Victoria, B.C., Canada, Aug. 16-19, 1993 (AAS Pubs., 1'0 Box 28130, San Diego, CA 92 198)

Yunck, 1'. 1'., Bertiger, w. 1., Wu, s. c, Bar-sever', Y., Christensen, E. l., Haines, B. J., Lichten, S. M., Muellerschoen, R. J., Vigue, Y., and Willis, 1'., "First Assessment of GPS-Based Reduced Dynamic Orbit Determination on TOPEX/POSEIDON," *Geophys. Res. Lett.*, vol. 21, pp. 54 I -544, 1994.

Zumberge, J., Neilan, R., Beutler, G., and Gurtner, w., "The international GPS Scrvicc for Geodynamics - Benefits to Users, " *Proceedings of ION GPS - 94 (7th International Technical Meeting of the Satellite Division of the Institute of Navigation),* Salt Lake City, Sept. 20-23, 1 994, pp.1 663-1606.